Chapter Two: The Hydrogeologic Environment

Cape Cod is a peninsula 440 square miles in area, developed from deposits of the last glaciation that separated Cape Cod Bay from the Atlantic Ocean. The peninsula runs 40 miles east-west from the Massachusetts coast into the Atlantic Ocean before turning to run 25 miles north-south. The upper Cape, or inner Cape, is the east-west portion of the peninsula, closest to the Cape Cod Canal and mainland Massachusetts. Cape Cod National Seashore is located on the north-south portion of the peninsula known as the lower or outer Cape. There is no exposed bedrock anywhere on Cape Cod. Depth to bedrock ranges from about 200 feet near the Cape Cod Canal to more than 900 feet in Truro (Oldale, 1980; 1992). Bedrock, therefore, plays little importance in the existing topography of National Seashore lands. Rather, glacial landforms and marine reworking of those landforms are evident everywhere.

The Cape Cod National Seashore consists of approximately 44,600 acres of uplands, ponds, wetlands and tidal lands. Inland, the National Seashore is dominated by rolling plains. The shoreline is dynamic in nature. It exhibits both cliffs, where storms are actively eroding the inland plains, and barrier beaches where the eroded material is redeposited. Strong coastal winds work the redeposited material into dunes. The dunes and associated wetlands on the lower Cape are one of the most distinctive visual landscapes of Massachusetts (Smardon,1972; Fabos, 1983).

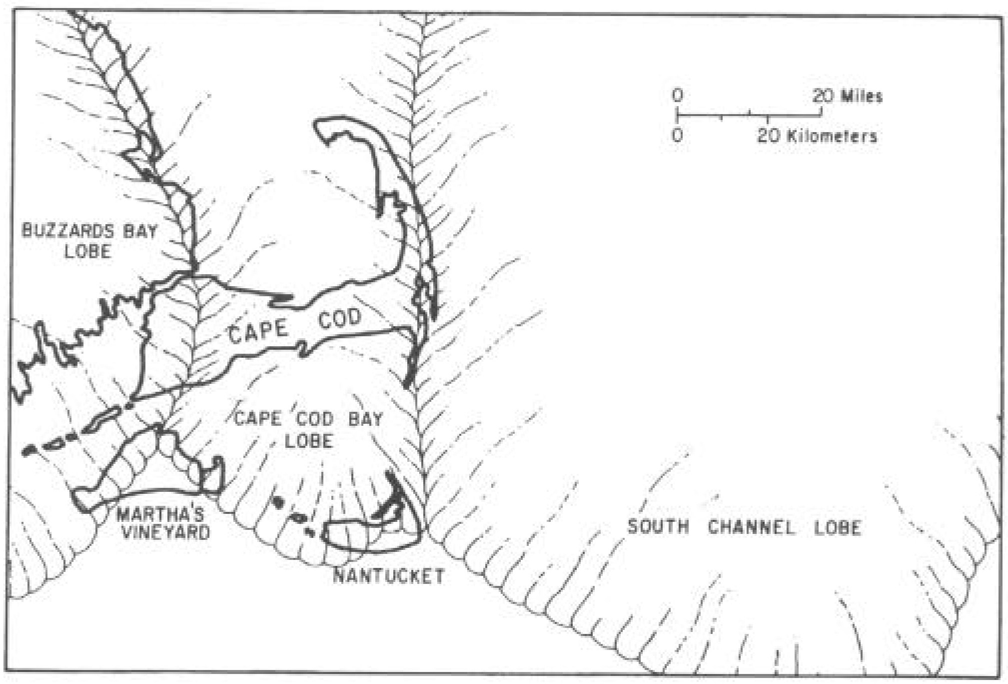
Geology

Most of Cape Cod was shaped by the last great glaciation in North America, the Wisconsin glacial stage of the Pleistocene, approximately 75,000 to 10,000 years ago. A vast ice sheet (the Laurentide ice sheet) advanced south from northern New England and Canada and transported eroded rock debris scoured from the underlying Paleozoic crystalline bedrock until it reached its southernmost limit at Martha's Vineyard and Nantucket Island. Late in this time period, the coalescing Buzzard's Bay, Cape Cod Bay, and South Channel glacial lobes of the Laurentide ice sheet deposited the glacial drift that now comprises much of Cape Cod (Oldale, 1980; 1992) (Figure 2.1).

The glacial history of the Cape Cod area was rapid in geologic terms. The minimum radiocarbon age of material found in the glacial drift indicates that the ice had reached Cape Cod more than 21,000 years ago. The maximum advance of the Laurentide ice sheet in the New England area is marked by the terminal moraines on Martha's Vineyard and Nantucket. At the time of maximum ice advance, sea level was about 300 feet lower than its present level, and the coastal plain extended far to the south of Cape Cod, out to the present edge of the continental shelf. South of the ice margin, meltwater streams flowed across the coastal plain to the sea (Oldale, 1980; 1992) (Figure 2.1). Retreat of the ice must have begun earlier than 18,000 years ago as the ice is thought to have retreated as far north as the Gulf of Maine by that time. This means that the ice had vanished from the Cape Cod area in less than 3,000 years and that most of Cape Cod's glacial landforms were created within about 1,000 years. Individual features may have formed in as little as several hundred years (Oldale, 1992).

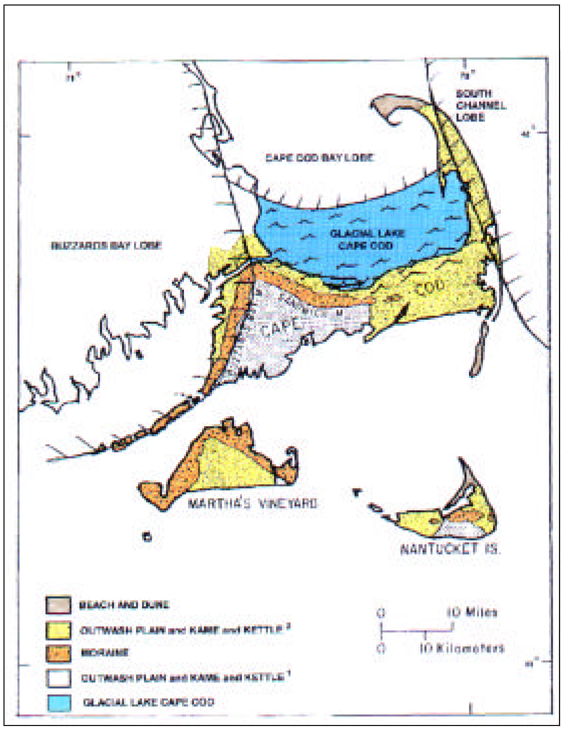
Through the interpretation of landforms, the relative timing of depositional events during glacial retreat has been fairly well determined. Forward progress of the ice sheet was often balanced by melting at the leading edge, so that the ice front maintained its position (ablation) even as it began to retreat. While the ice front was stationary, frequent warm periods caused large amounts of water to melt from the glaciers. The meltwater from the Buzzards Bay Lobe and Cape Cod Bay Lobe carried huge quantities of sediment from the glacier. This sediment formed the gently sloping outwash plains of stratified drift, several miles long, that now comprise much of the inner Cape (Oldale, 1992) (Figure 2.2). Minor re-advances of the ice sheets formed

Figure 2.1 Lobes of the late Wisconsin Laurentide ice sheet during its maximum advance in the Cape and Islands region (Oldale, 1980)



the thrusted Buzzards Bay and Sandwich Moraines located along the north and west margins of the upper Cape (Figure 2.2). No moraine deposits have been identified on the lower Cape.

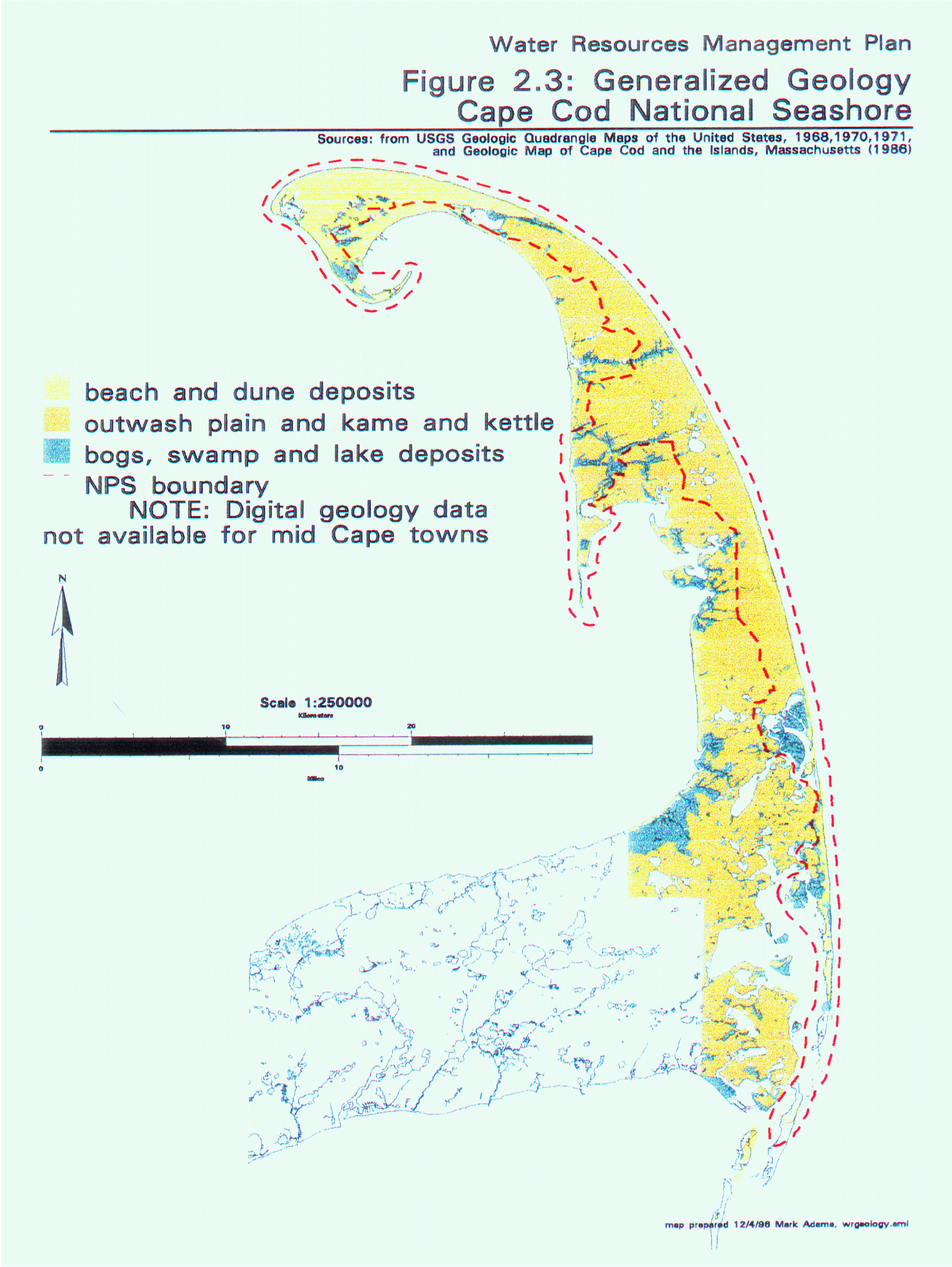
Figure 2.2. Glacial Lake Cape Cod (Adapted from Oldale, 1992).



When ice retreat resumed, the central Cape Cod Bay Lobe of the Laurentide ice sheet retreated faster than the surrounding lobes, and meltwater flooded the newly vacated lowlands to form glacial Lake Cape Cod in the area currently occupied by Cape Cod Bay. The lake was dammed to the north by the Cape Cod Bay Lobe, to the east by the South Channel Lobe, to the west by the Buzzards Bay Lobe, and to the south by the moraine and outwash plain deposits of Cape Cod (Figure 2.2). Fine grained clay and silt settled to the lake bottom leaving behind seasonal bands which together represent annual layers or varves as evidence for the lake in the Cape Cod Bay area. The lake periodically broke through the moraine and outwash deposits and partially drained. The escaping water left eroded lowlands, one of which would later be exploited for the construction of the Cape Cod Canal. The lake drained for the last time when both the Cape Cod Bay Lobe and the South Channel Lobe retreated far enough to allow the water to escape to the ocean (Oldale, 1980).

Later stagnations of the South Channel Lobe to the east of Glacial Lake Cape Cod allowed the four outwash plains of the lower Cape to be built. The Eastham, Wellfleet, Truro and the Highland outwash plains are the dominant morphologic features of the lower Cape. This outwash material was built up by deposits from braided meltwater streams flowing west into Glacial Lake Cape Cod. Isolated blocks of ice buried in the outwash deposits of both the inner and the lower Cape melted slowly, long after the glacial lobes had retreated far to the north. As sediments collapsed around the melting ice blocks, kettle holes formed within the outwash plains (Figure 2.3) (Oldale 1980; 1992).

After the last of the ice had retreated from the area, winds deposited eolian layers on top of the drift and sea level rose nearly 300 feet (Masterson and Barlow, 1994). Approximately 6,000 years ago, sea level rose high enough to flood Vineyard and Nantucket sounds. Marine reworking of the glacial sediments became an important process. The coastline was smoothed as glacial headlands were eroded back. Marine scarps were formed by the attack of storm surge waves, and the sediment was carried by long-shore drift to



Water Resources Management Plan
Figure 2.3: Generalized Geology
Cape Cod National Seashore
Sources: from USGS Geologic Quadrangle Maps of the United States, 1968,1970,1971,
and Geologic Map of Cape Cod and the Islands, Massachusetts (1986)
beach and dune deposits
outwash plain and kame and kettle
bogs, swamp and lake deposits
NPS boundary
NOTE: Digital geology data
not available for mid Cape towns
N
Scale 1:250000
0
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20
0
10
map prepared 12/4/98 Mark Adams, wrgeology.aml

form bars and spits. In the early period of deglaciation, sea level rise was about 50 feet per 1000 years. From 6,000 to 2,000 years ago, when most of the ice sheets had vanished, sea level rise had slowed to about 11 feet per 1000 years. Since then sea level rise has been approximately 3 feet per 1000 years. At the current rate of sea level rise, Cape Cod will continue to battle the waves for about another 5,000 years before succumbing to the sea (Oldale, 1980; 1992; Strahler, 1966).

Geomorphology

The landforms of the lower Cape are either glacially derived or a product of later marine and eolian reworking of glacial sediments (Oldale, 1980; 1992). Outwash plain deposits comprise the major geologic features of the lower Cape. They are predominantly stratified fine to medium sand and medium to coarse sand and gravel with lenses of fine silt and scattered boulders. Although lithologic variations over short distances can be extreme, grain size generally decreases with depth and distance from the former ice margin (Masterson and Barlow, 1994). Outwash plain surfaces are commonly pocked and pitted by kettle holes (e.g., the Wellfleet pitted outwash plain). When the kettles are deep enough to intersect the water table, a pond is formed. Thus pond level provides a close approximation of the water table. A kettle pond in Wellfleet yielded the oldest radiocarbon dated material at 12,000 years. (Winkler, 1985). This date, as much as 5,000 years after the ice retreated north, indicates that the buried ice blocks may have persisted for several thousand years after the glaciers retreated (Oldale, 1980; 1992).

Small streams and rivers, like the Pamet River, currently occupy oversized valleys within the outwash plains. The valleys were likely cut by ground water springs contacting the land surface at a time when a large pro-glacial lake, formed by large volumes of trapped meltwater, supported higher water tables. Later, with glacial retreat, catastrophic lake drainages enlarged the channels. Today, the streams appear undersized for the older valleys (Oldale, 1980; 1992).

The portion of Truro north of High Head and all of the Provincetown land area are not glacially derived. These areas consist of material derived from coastal erosion of the glacial outwash plains, transported northward, and redeposited by marine and eolian action as a series of recurved sand spits and dunes during the last 6,000 years (Ziegler et al., 1965).

Soils

The soils on the lower Cape are relatively young, having formed since the end of the last glaciation approximately 16,000 to 18,000 years ago. They exhibit only slight alteration of the original parent sand and gravel material and are well drained (U.S. Soil Conservation Service, 1993). Depth of soils on the Cape range from just a few inches in new dune and beach areas of the Province Lands to several feet in others; however, average depth is less than 6 inches. The soil on lower Cape Cod is predominantly a podzol, characteristic of climates that are both cold and humid. Cold temperatures inhibit bacteria and promote frost action, while humid conditions leach water soluble materials downward and support the growth of a vegetative cover (U.S. Soil Conservation Service, 1993; Oldale, 1992).
A podzol soil profile typically consists of an upper organic layer undergoing decay, a middle layer of mixed humus and mineral grains, and a lower layer of mostly mineral grains (Oldale, 1992). The historic cultivation

and burning of the land on the lower Cape, the associated current abundance of conifers, and the near shore ammonium loss through cation exchange with sea salts create acidic and nutrient poor soil conditions which contribute to stunted vegetative growth (Barnstable County Soil Survey, 1993; Brownlow, 1979; Blood et al., 1991; Valiela et al., 1997).

Soil type on the Cape is very important because it has a direct relationship to the rate at which infiltrating waters are purified. Soils which are coarse and sandy are highly permeable and allow effluent waters to travel quickly over large distances. Low organic matter and clay content provide little contaminant removal through soil sorption or cation exchange. Low organic content of the soils also decreases bacterial immobilization of nutrients as well as denitrification of nitrate-nitrogen. As a result, Cape Cod ground water is susceptible to contamination (Brownlow, 1979). According to the Barnstable County Soil Survey General Soil Map (1993), there are three principle soil types on the lower Cape: (1) *Carver* soil is characteristic of outwash deposits. It is the most common soil type on the lower Cape and is a poor filter for septic systems, sewage lagoons, and sanitary landfills.; (2) *Hooksan-Beaches-Dune Land* soil is characteristic of wind-blown deposits found in the Province Lands and on beaches. It is a poor filter for septic systems, sewage lagoons, and sanitary landfills.; (3) *Ipswich-Pawcatuck-Matanuck* soil is poorly drained and limited to lowland areas (e.g., the Pamet River, Little Pamet River, Herring River and Salt Meadow) (Figure 2.4). It has flooding and ponding potential when used for septic systems, sewage lagoons, and sanitary landfills.

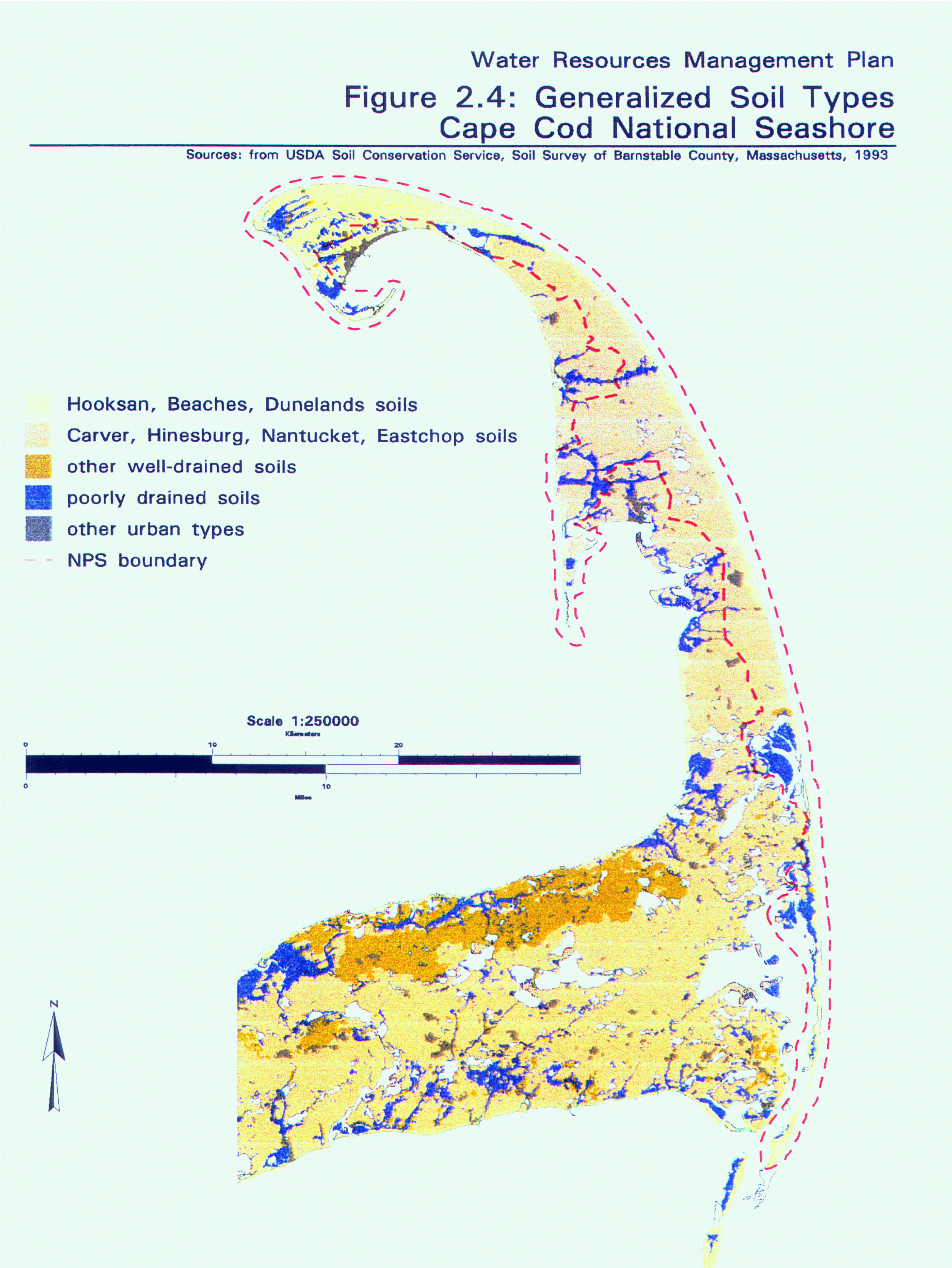
Topography

The topography of the lower Cape between Orleans and North Truro is defined by four pitted outwash plains and is fairly flat. The maximum elevation is 120 feet above sea level at Highland Light. The high ground occurs on the sand cliffs on the Atlantic shore and slopes gradually down to the west. On a local scale, topographic highs and lows are marked by knobs and kettles within the outwash plains. This topography is characteristic of the lower Cape. Kettle holes form inland freshwater ponds, wetlands, and coastal bays and marshes when their depth is below the existing water table (Oldale, 1992).

Climate

Cape Cod has a north temperate maritime climate that is characterized by well defined summer and winter seasons. Summer temperatures reach average highs of 77.5 degrees Fahrenheit and average lows around 61 degrees Fahrenheit. The winter months range from an average of 38 degrees Fahrenheit to 24 degrees Fahrenheit (Urish et al., 1993). Due to the moderating effects of the ocean, the Cape temperatures are on average two to three degrees Fahrenheit cooler in the summer and several degrees warmer in the winter compared to mainland temperatures. The average growing season, between the first and the last killing frosts, is 200 days, considerably longer than most inland locations (Strahler, 1966).

Average precipitation on Cape Cod varies from about 40 inches per year on the lower Cape to 45 inches per year near the Cape Cod Canal. In the 1960s and1970s, total annual precipitation on the lower Cape ranged from a low of 26.5 inches to a high of 66


Water Resources Management Plan
Figure 2.4: Generalized Soil Types
Cape Cod National Seashore
Sources: from USDA Soil Conservation Service, Soil Survey of Barnstable County, Massachusetts, 1993
Hooksan, Beaches, Dunelands soils
Carver, Hinesburg, Nantucket, Eastchop soils
other well-drained soils
poorly drained soils
other urban types
NPS boundary
Scale 1:250000
Kilometers
0
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map prepared 12/4/96 Mark Adams, wrsoils.aml

inches. Winds on the Cape, predominantly from the northwest in the fall and winter and southwest in the summer, impact the formation of the lower Cape significantly as they are the primary building force for dune fields. When winds from the northeast bring storms, east facing shorelines can suffer from significant erosion produced by the energy of the storm (Brownlow, 1979).

GROUND WATER

The Hydrologic Cycle

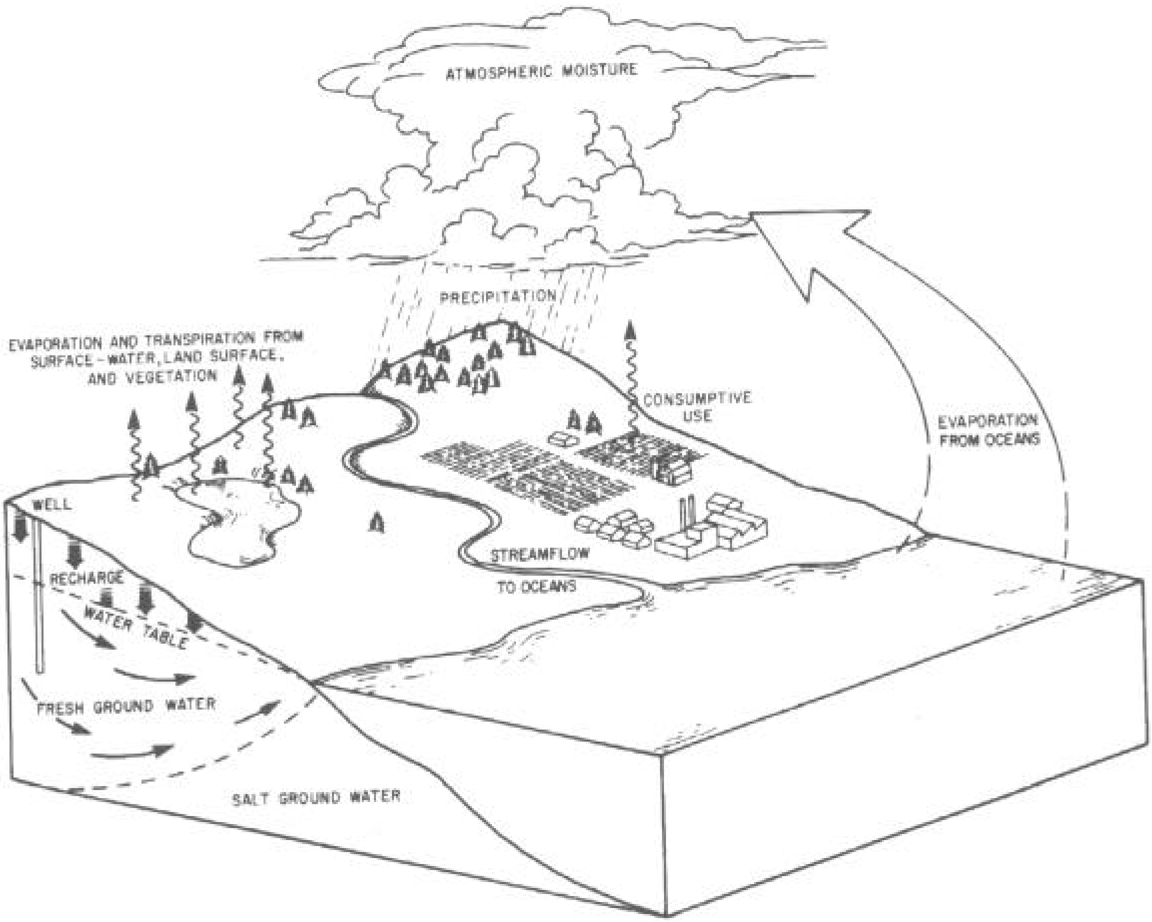
About half the precipitation falling on the lower Cape is returned directly to the atmosphere by evaporation and by plant transpiration (See Figure 2.5). The remaining half rapidly infiltrates the permeable sand and gravel stratified drift of the lower Cape outwash plains, where it fills the voids between unconsolidated mineral grains. On the lower Cape, all ground water has local precipitation as its source. As evidenced by the absence of any significant surface drainage features, less than 1 percent of all precipitation collects as overland runoff to streams and ponds (Wilson and Schreiber, 1981; LeBlanc et al., 1986). Once in the subsurface, the water flows down gradient between the pore spaces in the sedimentary deposits, and under the influence of gravity, it eventually enters the ocean (Oldale, 1992; Nemickas et al., 1989) (Figure 2.5). Water evaporates from the ocean surface to atmospheric water vapor, which condenses to fall again as rain or snow.

Hydrogeology

Geologic materials that are saturated with abundant freshwater are called aquifers. The ability of a material to hold and transmit water is largely dependent on its porosity, that is the number, size, and interconnectedness of the pore spaces between particles. Deposits consisting primarily of large sized sand and gravel particles (e.g., outwash deposits) transmit more water than deposits of finer grained silt and clay size deposits (e.g., lake deposits). Well sorted, stratified sediments (e.g., outwash deposits) are not so easily compacted and are described as having a high hydraulic conductivity or transmissivity (Fetter, 1994). Poorly sorted sediments of mixed grain sizes (e.g., till) have a poor capacity to transmit water because the smaller particles fill the voids between the larger particles.

The thick, glacial sand and gravel outwash plain of the lower Cape can be thought of as a huge sponge with a large capacity for water storage. Precipitation on the land surface easily percolates down through the soil until it comes to a level saturated with water. This level is the water table. Pore space above the water table, where water and air mix, is known as the unsaturated zone. Below the water table is the ground water or saturated zone, where all pore space is completely filled by water. An unconfined aquifer is one in which the water table forms the upper boundary (Freeze and Cherry, 1979). A confined aquifer is one that lies between two layers of geological material having very poor capacity to transmit water, such as silt and clay. Unconfined aquifers occur near land surface, whereas confined aquifers tend to occur at depth. Most of the ground water on the lower Cape occurs under unconfined conditions, although there are small areas of confinement in the vicinity of localized silt and clay lenses (Strahler, 1966). Lenses of silt and clay commonly exhibit conductivities of less than 1 foot per day creating a serious impediment to vertical flow (Martin, 1993).

Figure 2.5. The Hydrologic Cycle. Fresh water on the Cape depends solely on the precipitation that falls locally. There is no underground river bringing fresh water to Cape Cod (Oldale, 1992).



The outwash deposits present by far the best opportunities for ground water development on the lower Cape. They are not only thick, but consist of sand and gravel which has high hydraulic conductivities of 100 to 500 feet per day and provides excellent well yields. In these conditions, two foot diameter wells with a 10 foot screened length commonly yield 250 to 1000 gallons per minute (LeBlanc et al., 1986; Guswa and LeBlanc, 1981).

Thousands of years of melting glacial water and precipitation have built up four distinct subsurface reservoirs of fresh ground water hundreds of feet thick on the lower Cape. Since fresh water is less dense than salt water, rain infiltrating the subsurface rests atop and depresses the surface of the salt water. In each of the lower Cape's four aquifers, a lens-shaped body of fresh water exists, which is thickest at its center. A vertical cross section of the lower Cape's aquifers would show that the fresh and salt waters meet on a surface that starts near the shoreline and slopes steeply down below the center of the peninsula from both sides (Figure 2.5). The upper surface of the freshwater lens, defined by the water table, is convex up and the lower surface, defined by the fresh water-salt water interface, is convex down. The maximum thickness of fresh water, therefore, is toward the center of each lens (Oldale, 1992). The top of the aquifer is marked by the water table and the bottom by the contact between fresh and salt water (depth to bedrock on the lower Cape is far below the deepest extent of fresh water).

The Ghyben-Herzberg principle states that in unconfined coastal aquifers, the fresh ground water will extend below mean sea level about forty times deeper than the height that the water table rises above mean sea level. This principle is based on a mathematical relationship between the relative densities of fresh and salt water (Fetter, 1994), and can be applied to Cape Cod ground water. For example, in Wellfleet, water levels in the ponds are about 8 feet above sea level, and fresh ground water extends to about 320 feet below sea level. Freshwater lenses are as much as 200 feet thick in Truro, 250 feet thick in Wellfleet, and 275 feet thick in Eastham (Oldale, 1992).

The water table on the lower Cape is not a perfectly horizontal surface, but has a gentle slope or hydraulic gradient. Ground water moves slowly down slope under the influence of gravity. The lower the hydraulic conductivity of the materials through which the water seeks to travel, the greater the energy required to accomplish that movement and the steeper the resultant slope of the water table. Flow through the very highly conductive materials of the lower Cape outwash plains requires very little hydraulic gradient. Therefore, the slope of the water table is less steep than it would be in less conductive materials. The highest ground water levels occur in the center of each ground water lens and create a linear band of high water table along the center of the outer Cape. The hydraulic conductivity in localized areas of silt and clay may be several orders of magnitude less and produce a steeper hydraulic gradient (Oldale, 1992). Ground water flows slowly and radially from higher areas to lower areas down-gradient towards the perimeter of the aquifer where it finally discharges to the sea, salt water bays, inlets, canals and streams (Figure 2.5) (Oldale, 1992; Strahler, 1966).

Ground Water Recharge

Ground water recharge occurs over the entire land surface of the lower Cape. The highly permeable soils allow precipitation access to the subsurface equally in all areas. However, since ground water flows radially from water table highs near the center of the aquifers to water table lows at the perimeters, principal recharge areas are generally near the centers of the ground water mounds. Ground water originating in these areas will spend more time in the aquifer than that originating near the periphery of the aquifer. In recharge areas, flow is predominantly downward. Most ground water recharge on the lower Cape occurs during the late fall, winter and spring when precipitation is high and evapotranspiration is low (Guswa and LeBlanc, 1981). Recharge has not been directly measured, but an average rate of 18 inches per year has been used by most previous investigators. This estimate is based on the empirical Thornthwaite method (Thornthwaite and Mather, 1957) which relates recharge to climatological data.

Essentially, the average yearly recharge is equal to the average yearly precipitation less that lost to evapotranspiration and direct overland runoff. On the lower Cape, annual recharge variability does tend to follow annual precipitation variability. The lower Cape, along with the rest of the northeast, suffered a drought in the mid-1960s from which it recovered in the 1970s. The years from 1964 to1966 experienced the least precipitation and show record low water levels. The years from 1972 to 1973 were unusually wet and show record high water levels (Guswa and LeBlanc, 1981; LeBlanc, 1986).

Recharge may be locally reduced due to small scale variability of evapotranspiration and the presence of man-made impermeable surfaces. High evapotranspiration occurs over ponds and other areas where the water table is close to or at the surface. Pond evapotranspiration rates are estimated to be about 28 inches per year on the lower Cape. Therefore, net aquifer recharge under ponds is about 12 to 16 inches per year depending on the local precipitation rate (Guswa and LeBlanc, 1981). Impermeable surfaces such as pavement and roofs channel precipitation directly to storm drains, streams, and the ocean. Wastewater treatments plants, though not presently operational nor even proposed for the National Seashore towns, also decrease recharge if effluent is directly discharged into the ocean. Artificial runoff is a net loss of recharge (Ryan, 1980).

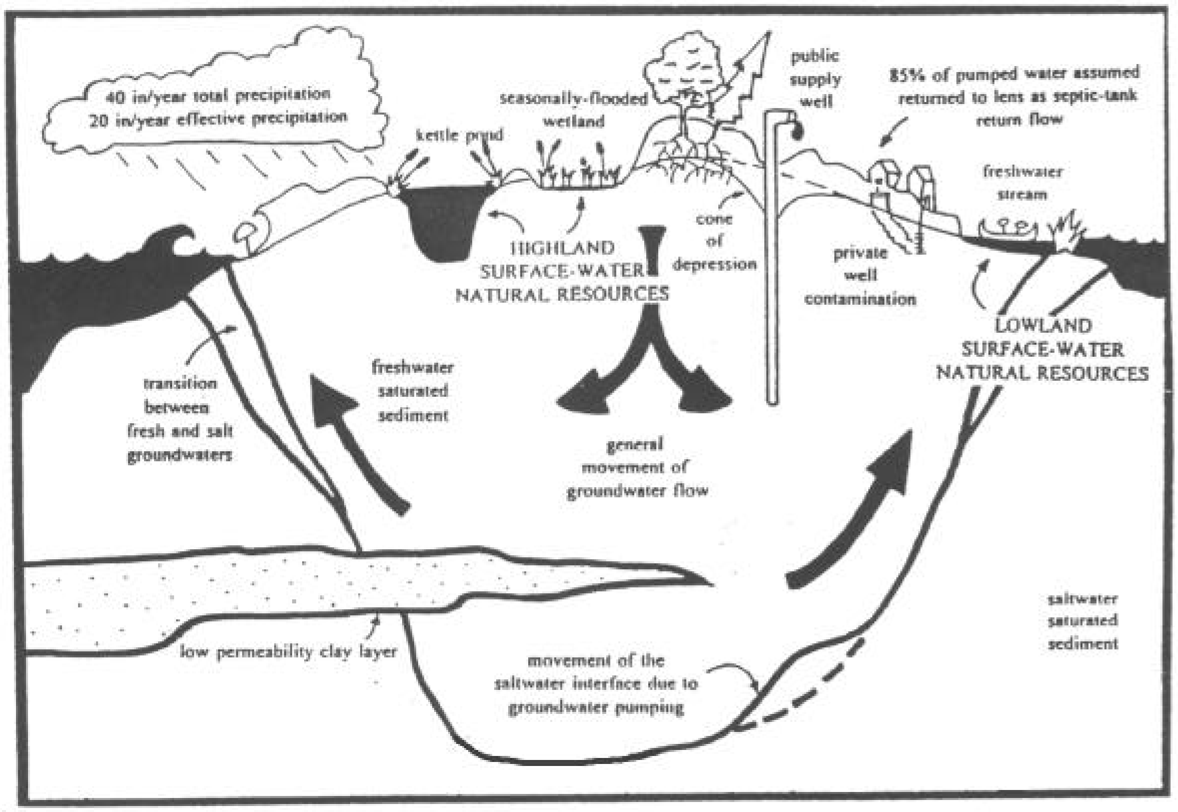
Ground Water Discharge

Any water entering the aquifer will eventually leave the aquifer as ground water discharge to streams, wetlands, wells, springs, and the ocean near the lateral boundaries of the aquifer (Massachusetts Department of Environmental Management, 1994). In addition, discharge by evapotranspiration can be significant in ponds and low lying areas when the water table is very near the surface and plant roots reach the saturated zone. In discharge areas flow is predominantly upward (Figure 2.6) (LeBlanc et al., 1986). Many specific ecosystems in these areas are dependent on sustained ground water discharge volume. Stream flow is also maintained by fresh ground water discharge. Estuary and marsh environments depend on fresh ground water input to maintain the proper salinity, pH, and water chemistry (Martin, 1993). Freshwater discharge to high energy shoreline environments, although insignificant in terms of salinity balance and water levels (Martin, 1993), does control the position of the fresh water-salt water interface (Fetter, 1994), and likely influences near-shore pore water chemistry and related interstitial fauna (Portnoy, 1996, personal communication, National Park Service).

Ground Water Levels

The altitude of the water table is controlled by a variety of factors: proximity to discharge areas, areal distribution of recharge, artificial recharge, proximity to pumping wells, hydraulic conductivity of the sediments, and seasonal and long-term recharge variability. Ground water fluctuations are generally smallest near the shore and greatest inland. In contrast, coastal areas are the most responsive to the loading and unloading effects of diurnal tidal fluctuations. Tidal influences cause fluctuations of fresh ground water levels similar to, but more subdued than, those of the sea water. Tidal effects dissipate rapidly away from the coast. An observation well 500 feet

Figure 2.6. Inland/Coastal Surface to Water Natural Resource Relationships (modified from Sobczak and Cambareri, 1995).



from Wellfleet Harbor exhibited tidal effects one-sixth those experienced in the harbor (LeBlanc et al., 1986). Seasonal high levels occur in early spring and low levels in the fall.

Unless they are perched on low permeability sediments, the vast majority of the lower Cape's ponds and wetlands are connected hydraulically to the ground water flow system and are an expression of the water table at that location. Compared to other parts of the aquifer, water table elevations across ponds are relatively flat because there is little resistance to flow. Water table contours follow the natural gradients of the pond, bending up at the up-gradient end and down at the lowest gradient of the pond. This shape focuses ground water inflow into the up-gradient ends of ponds and disperses pond water outflow to the surrounding aquifer at the down-gradient ends. Consequently, ponds are often areas of ground water through-flow (Barlow, 1994a).

The Flow System

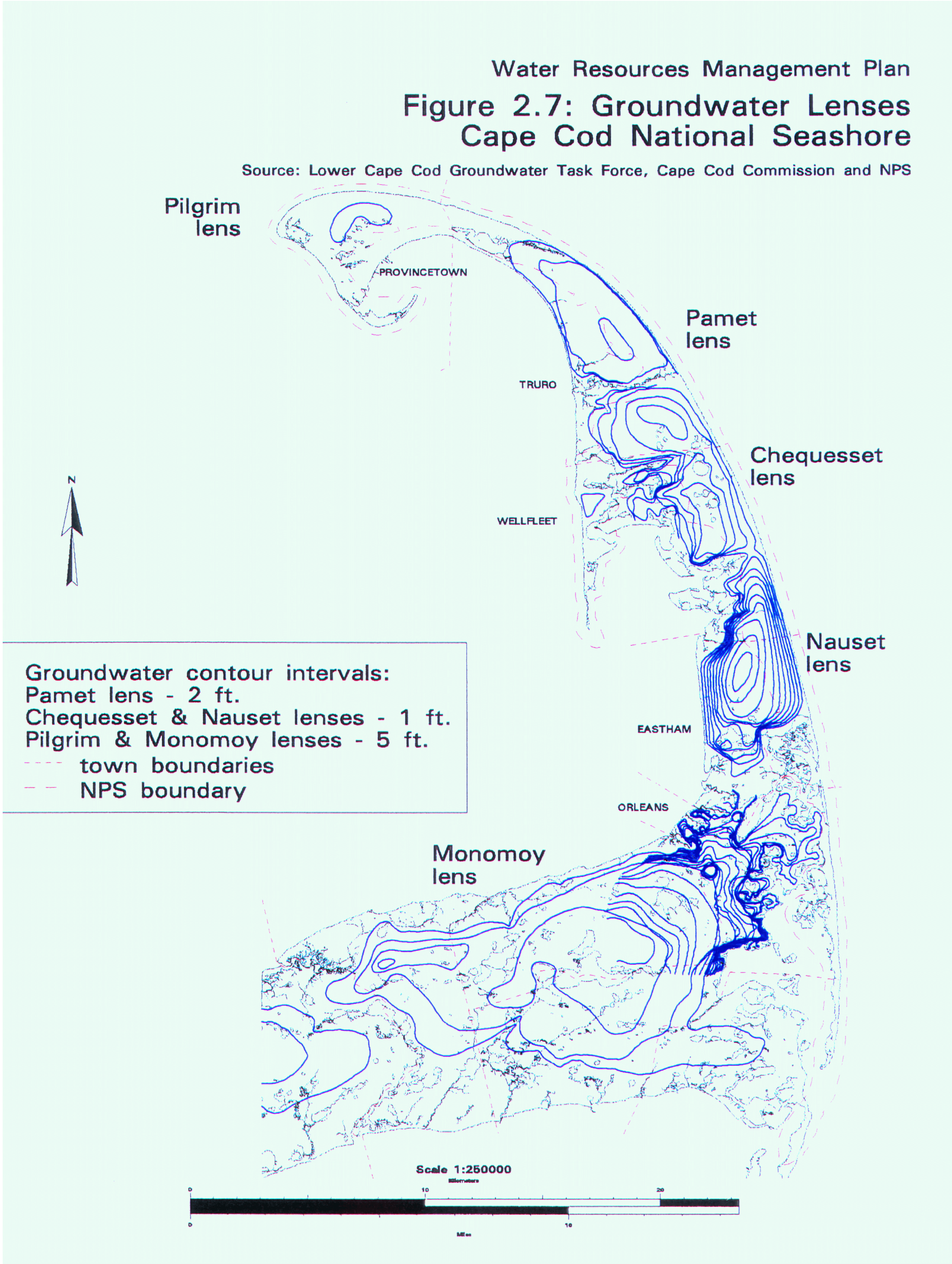
The Cape Cod aquifer system consists of six distinct ground water reservoirs called ground water lenses or flow cells. The land area over each flow cell constitutes its recharge area. The lenses are separated from each other by bays, marshes, streams and glacial outwash valleys which constitute the discharge areas. Four of these flow cells are located on the lower Cape (Figure 2.7). Each flow cell is characterized by a ground water mound.

Under natural conditions, the flow cells or ground water lenses, are physically in contact with each other but hydraulically separate. Ground water elevations, movement, and water quality in one flow cell do not affect neighboring flow cells (Martin, 1993), though some interconnections may develop at times of extreme drought or other stress on the aquifer system (Guswa and LeBlanc, 1981). Under natural conditions, a ground water lens is assumed to be in a state of dynamic equilibrium. The equilibrium is dynamic because seasonal and annual fluctuations in precipitation and recharge result in corresponding fluctuations in water level and discharge. Over the long-term, however, the amount of water entering the lens as recharge is balanced by the amount leaving as freshwater discharge; the natural system is balanced (Sobczak and Cambareri, 1995). Vertical boundaries of the lower Cape flow cells are the water table at the top and the freshwater/saltwater interface at the bottom.

The U.S. Geological Survey and Cape Cod Commission use different names to describe the six flow cells on the Cape. The Cape Cod Commission nomenclature follows in parentheses and is used predominantly in this report. The West Cape (Sagamore) flow cell underlies the towns of Barnstable, Bourne, Falmouth, Mashpee, Sandwich and Yarmouth; the East Cape (Monomoy) flow cell underlies the towns of Orleans, Brewster, Chatham, Harwich, Dennis, Yarmouth, and the southern part of Eastham; the Eastham (Nauset) flow cell underlies the northern part of Eastham, the southern part of Wellfleet, and 38 percent of the areal extent of the lens is within the National Seashore; the Wellfleet (Chequesset) flow cell underlies northern Wellfleet, southern Truro, and 70 percent of the areal extent of the lens is within the National Seashore; The Truro (Pamet) flow cell contains northern Truro and 54 percent of the areal extent of the lens is within the National Seashore; the Provincetown (Pilgrim) flow cell underlies very northern Truro, Provincetown, and 80 percent of the areal extent of the lens is within the National Seashore (Figure 2.7). Only the Sagamore, Monomoy, Pamet, and Chequesset cells currently contain public water supplies (Oldale, 1992).

Nauset Lens

The Nauset lens is the southern-most of the lower Cape flow systems (Figure 2.7). No public water supplies are currently located here. The aquifer consists of an upper, 100 foot thick unit of sand and gravel above a greater than 300 foot thick lacustrine unit of fine to very fine sand, silt and clay. The fresh water-salt water interface is within the fine-grained unit 200 to 300 feet below sea level and well above the bedrock contact. The conductivity contrast between the coarse and fine unit is considered so great that in models of this lens, very little water flows through the fine grained unit (Barlow, 1994b).


Water Resources Management Plan
Figure 2.7: Groundwater Lenses
Cape Cod National Seashore
Source: Lower Cape Cod Groundwater Task Force, Cape Cod Commission and NPS
Pilgrim lens
PROVINCETOWN
Pamet lens
TRURO
Chequesset lens
WELLFLEET
N
Nauset lens
Groundwater contour intervals:
Pamet lens - 2 ft.
Chequesset & Nauset lenses - 1 ft.
Pilgrim & Monomoy lenses - 5 ft.
town boundaries
NPS boundary
EASTHAM
ORLEANS
Monomoy lens
Scale 1:250000
0
10
20
0
10

The southern edge is at the Town Cove and Boat Meadow River area just north of the Eastham / Orleans border and the northern limit is at Blackfish Creek. The land surface over the Nauset lens is approximately 3 miles across at its widest point and 7 miles long. The average maximum ground water elevation is 18 feet above mean sea level (Massachusetts Department of Environmental Management, 1994). Ground water elevations have fluctuated a maximum of 5.5 feet from the wettest season to the driest season on record (1975 to 1987) (Janik, 1987; Massachusetts Department of Environmental Management, 1994).

Chequesset Lens

The Chequesset aquifer is immediately north of the Nauset lens (Figure 2.7). It lies beneath the southern third of Truro and the northern two-thirds of Wellfleet. The southern Boundary is at Blackfish Creek and the northern boundary is the Pamet River. Geologic conditions are similar to the Nauset lens. There are currently no large volume public water supplies and only one small volume public well supplying approximately 30 households in the Coles Neck area of Wellfleet. The land surface over the Chequesset lens is approximately 3 miles across at its widest point and 6 miles long. The average maximum ground water elevation is 8 feet above mean sea level (Massachusetts Department of Environmental Management, 1994). The annual range of ground water levels in the Chequesset lens is approximately 2 to 3 feet (Cambareri, 1986). Ground water elevations have fluctuated a maximum 6 feet from wettest to driest season on record 1978 to1987 (Janik, 1987).

Pamet Lens

The Pamet lens is immediately north of the Chequesset lens (Figure 2.7). It lies beneath the northern two-thirds of Truro. The Pamet lens also has a similar geologic setting as the Nauset and Chequesset aquifers. The southern boundary is Pamet River and the northern boundary is the Pilgrim Lake and Salt Meadow area. The land surface over the Pamet lens is approximately 2.75 miles across at its widest and 6 miles long. Average maximum elevation of the water table in the Pamet aquifer is 6 feet above mean sea level (Mass. Department of Environmental Management, 1994). The annual range of ground water levels in the Pamet lens is approximately 2 to 3 feet (Cambareri, 1986). Maximum ground water fluctuation has been 3.5 feet between the wettest and driest periods on record 1973-1987 (Janik, 1987). The Pamet lens is the only lower Cape aquifer currently utilized for large volume public water supply. The Pamet lens serves as the water supply for the Towns of Truro and Provincetown, the North Truro Air Force Base Station (now closed) and the National Seashore (Cambareri, 1986). It is the most sensitive of the lower Cape's aquifer systems due to its small size, its equilibrium with surrounding sea water, and the withdrawal demands placed upon it (Massachusetts Department of Environmental Management, 1994).

Pilgrim Lens

The Pilgrim lens is the farthest north of the lower Cape flow systems (Figure 2.7). It underlies Provincetown and extends south to the Pilgrim Lake / Salt Meadow area in Truro. The land area over the Pilgrim lens is approximately 3 miles across at its widest and

7 miles long. The average maximum water table elevation is 5 feet above mean sea level (Mass. Department of Environmental Management, 1994). It is the only lower Cape aquifer not contained within glacial outwash deposits. Marine reworking of the lower Cape highlands has created a recurved spit covered with eolian sand dunes. This material constitutes the aquifer matrix. The Pilgrim lens has naturally high levels of iron, manganese and chloride, perhaps resulting from the formation and subsequent burial of many wetland areas as sand accumulated at the tip of Cape Cod. The poor water quality and the very high development density in Provincetown account for the absence of any public or private drinking water withdrawal from the Pilgrim lens. Instead Provincetown imports its water supply from the Pamet lens (Cambareri, 1986). The Pilgrim lens has been omitted from most ground water studies due to its lack of existing or potential drinking water supplies.

Ground Water Contamination

Ground water on the Cape is withdrawn from shallow sand and gravel aquifers that are susceptible to contamination from anthropogenic sources (Oldale, 1992). The generally shallow depth to the water table minimizes the time and distance required for contaminants to reach the ground water. Once in the subsurface, contaminants tend to move in a plume shape following ground water flow patterns. Contaminants are spread by advection, physical transport in the direction of ground water flow, and dispersion, mixing of the dissolved components with the surrounding water in three dimensions. The movement of contaminants is retarded by adsorption, the process by which dissolved components in the ground water adhere to particles in the aquifer matrix, and both chemical and biochemical reactions between the contaminant and other aquifer components (LeBlanc, 1984). Ion exchange, the process by which ions in the ground water substitute for similarly charged ions in the aquifer matrix, is the most common of chemical and biochemical reactions. The sandy soils of the lower Cape are low in organic content and have a poor capacity for attenuating contaminants by either adsorption or ion exchange (Weiskell et al., 1996; Zoto and Gallagher, 1988). A 1984 study of a sewage plume at Otis Air Force Base on the upper Cape, concluded that conservative ions such as boron, sodium, and chloride move rapidly through the subsurface under the influence of advection and dispersion (LeBlanc, 1984). Phosphorus was found to be greatly restricted by adsorption. Nitrogen in the form of ammonium was biochemically oxidized to nitrate through a reaction with dissolved oxygen in the ground water. Nitrogen in the form of nitrate moved freely through the subsurface under the influence of advection and dispersion (LeBlanc, 1984).

There are three principal types of pollutants impacting the ground water resources of the lower Cape: organic, inorganic, and biological. Organic pollutants contain carbon in their structures and are generally related to the petroleum products or solvents that are ubiquitous in modern, industrial society. Possible mechanisms for entrance to the ground water range from leaking underground storage tanks and illegal dumping to the use and disposal of household cleaning supplies and septic system cleaners (Janik, 1987; Cape Cod Planning and Economic Development Commission, 1978). Inorganic pollutants are those that do not contain carbon in their structure. The most common inorganic pollutants in Cape Cod ground water are ammonium (NH_4), nitrate (NO_3), sodium (Na), and phosphorus (P). These components can enter the subsurface through septic system waste water, landfills, and road runoff. Nitrate and sodium are the two most prevalent inorganic pollutants in Cape Cod ground water (Janik, 1987). Biological pollutants include viruses, bacteria, and protozoans associated with human fecal matter. The biological pollutant most tested for is coliform bacteria, whose presence may indicate the presence of pathogenic organisms. Ground water contamination issues specific to the outer Cape are discussed in later chapters.